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(54) **RF DEVICE WITH COMPENSATORY
RESONATOR MATCHING TOPOLOGY**

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(52) **U.S. Cl.**
USPC **330/302**; 330/295; 330/124 R

(58) **Field of Classification Search**
USPC 330/302, 295, 124 R, 286
See application file for complete search history.

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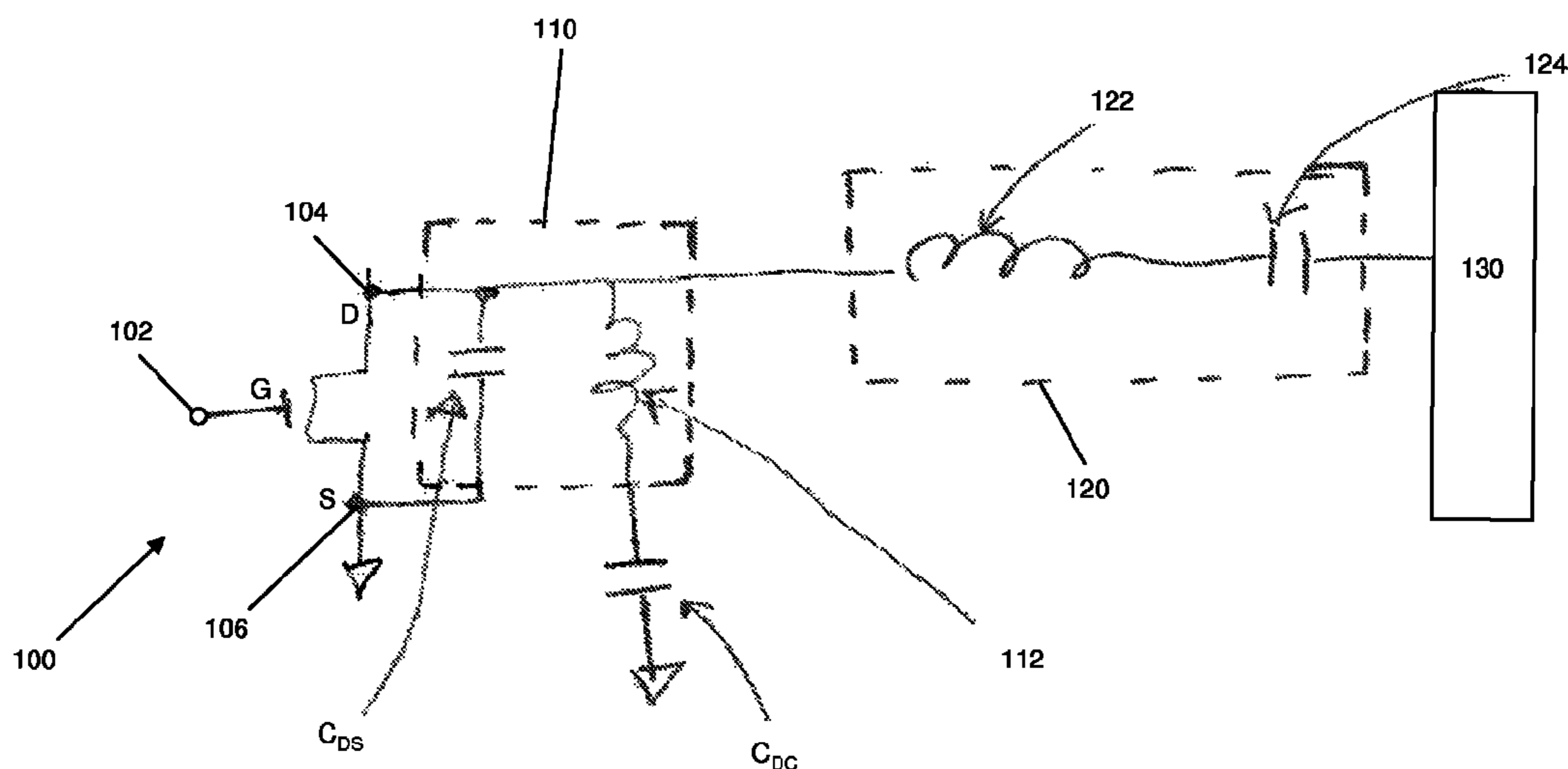
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PLLC

(57) **ABSTRACT**

An amplifier circuit includes an RF transistor, a parallel reso-
nator and a series resonator. The RF transistor has an input, an
output and an intrinsic output capacitance. The parallel reso-
nator is connected to the output of the RF transistor and
includes a first inductive component connected in parallel
with the intrinsic output capacitance of the RF transistor. The
series resonator connects the output of the RF transistor to an
output terminal and includes a second inductive component
connected in series with a capacitive component. The series
resonator is operable to compensate for a change in imped-
ance of the parallel resonator over frequency.

17 Claims, 7 Drawing Sheets



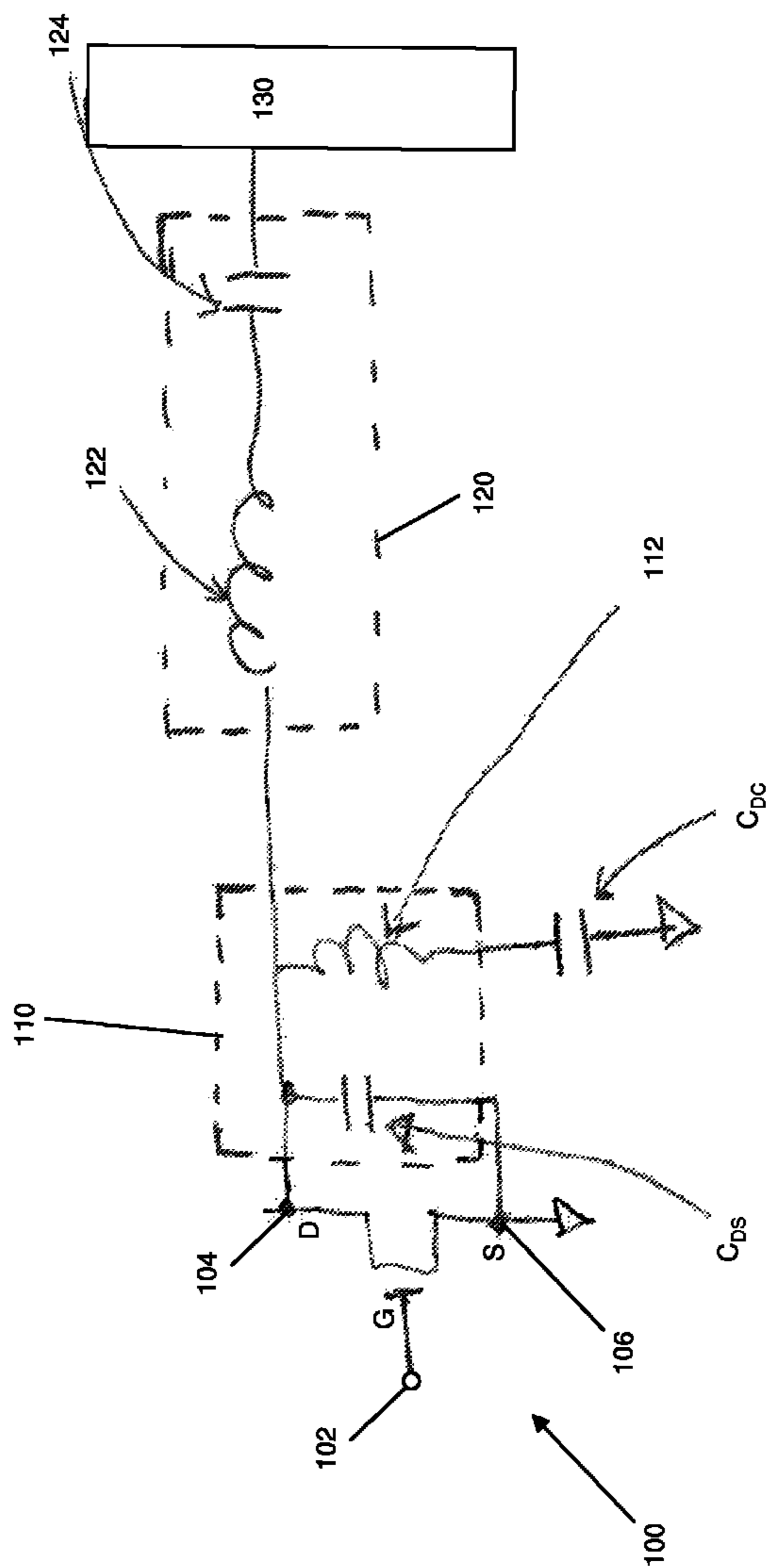


Figure 1

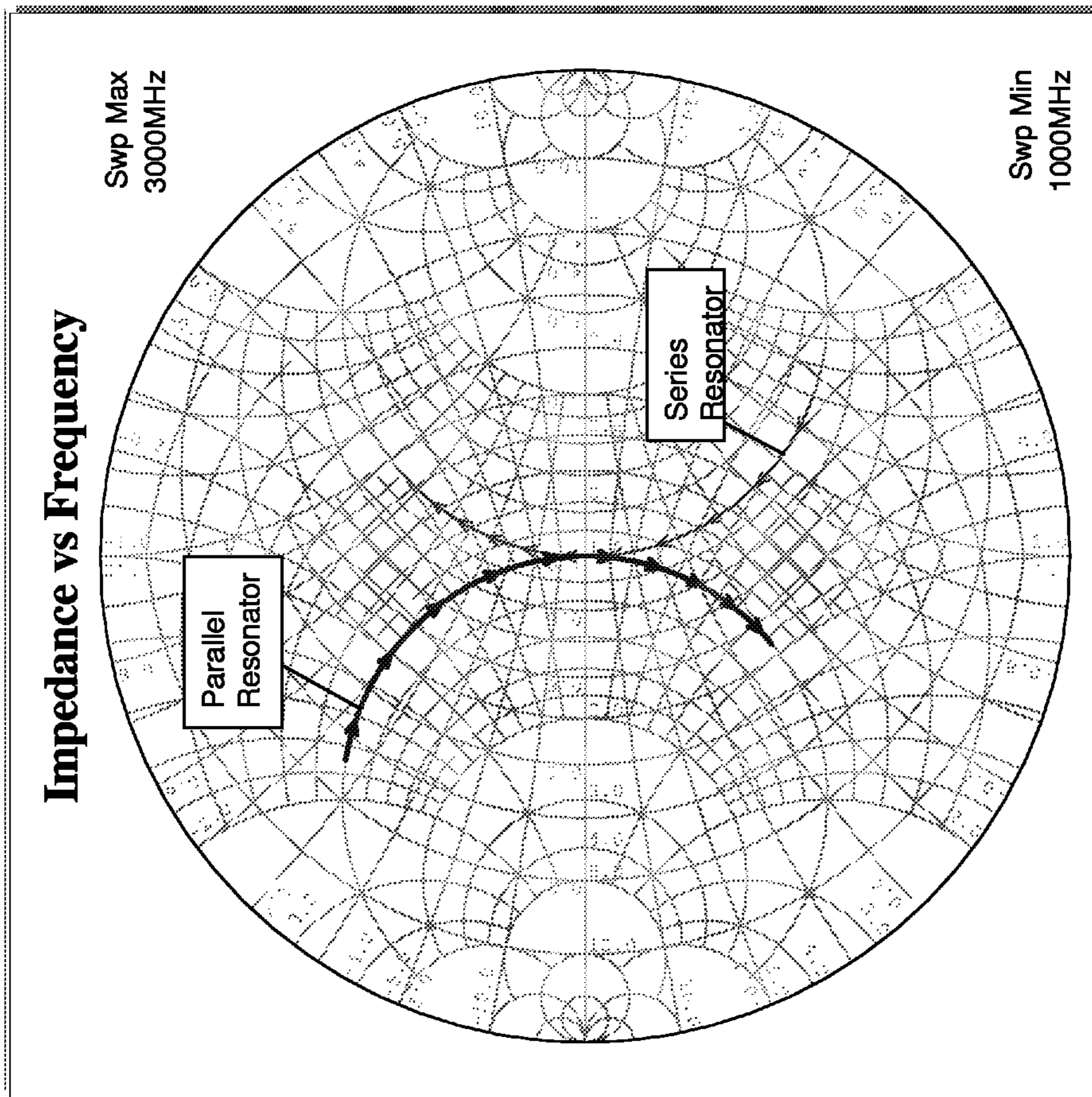


Figure 2

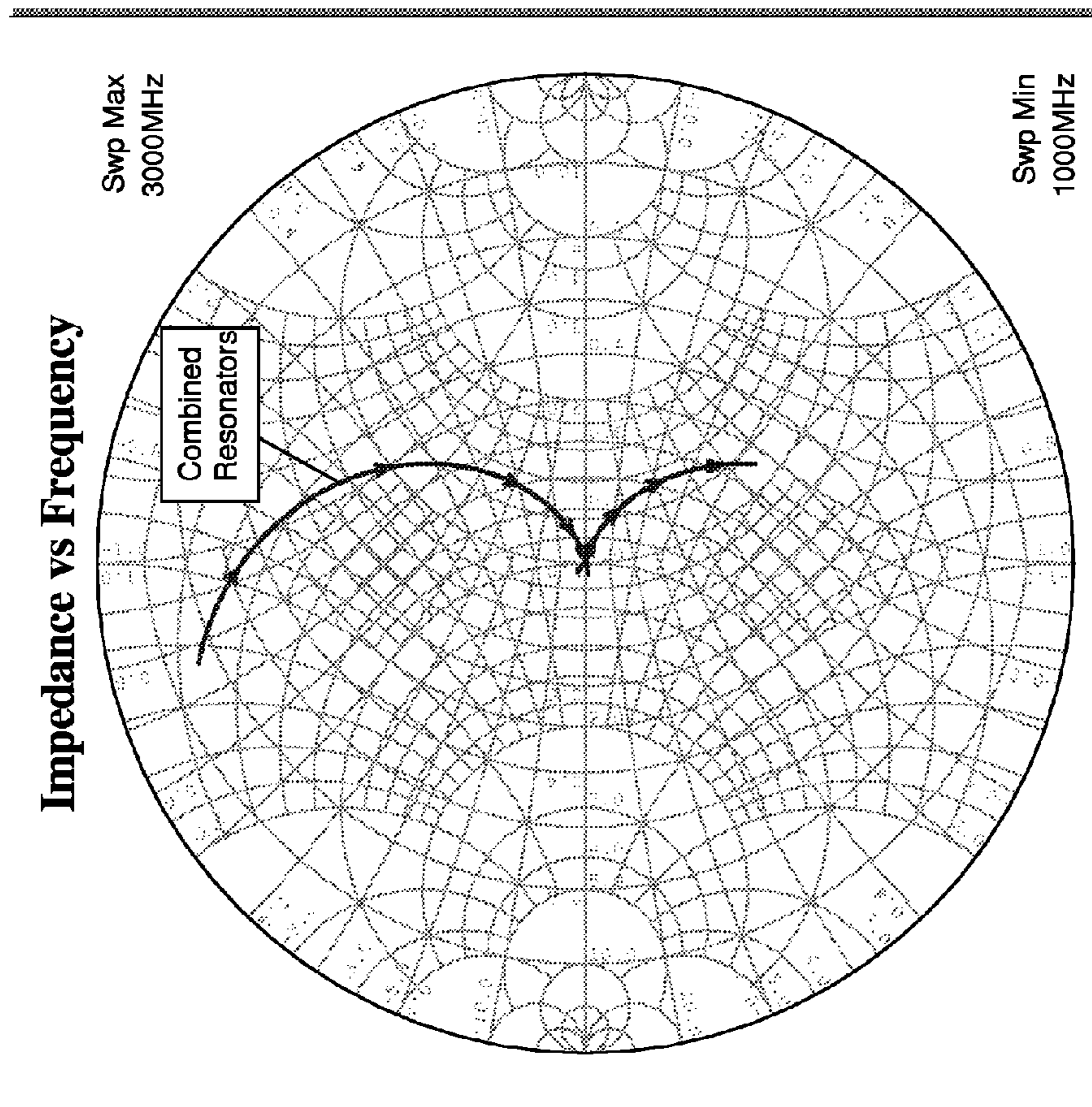


Figure 3

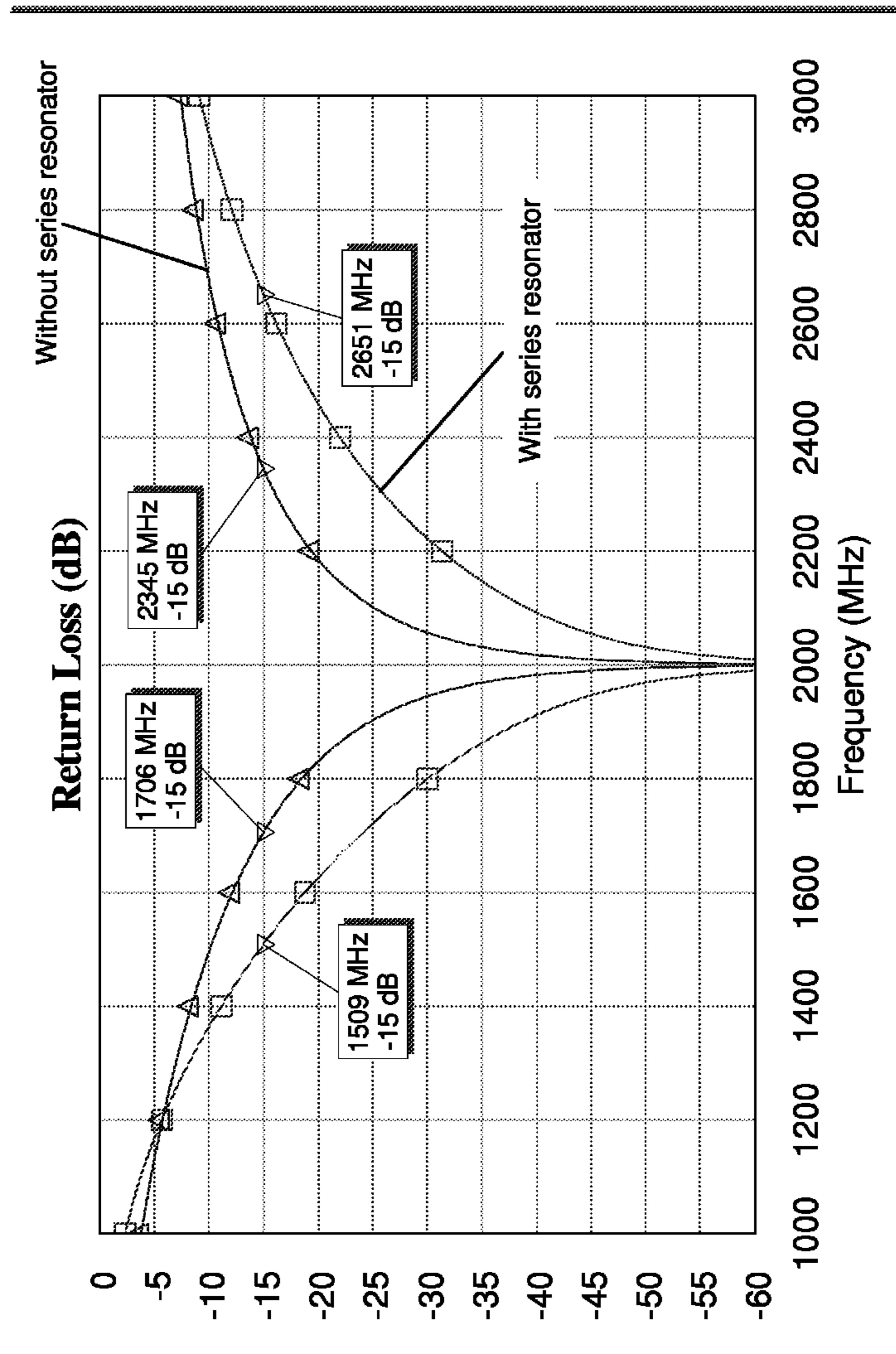


Figure 4

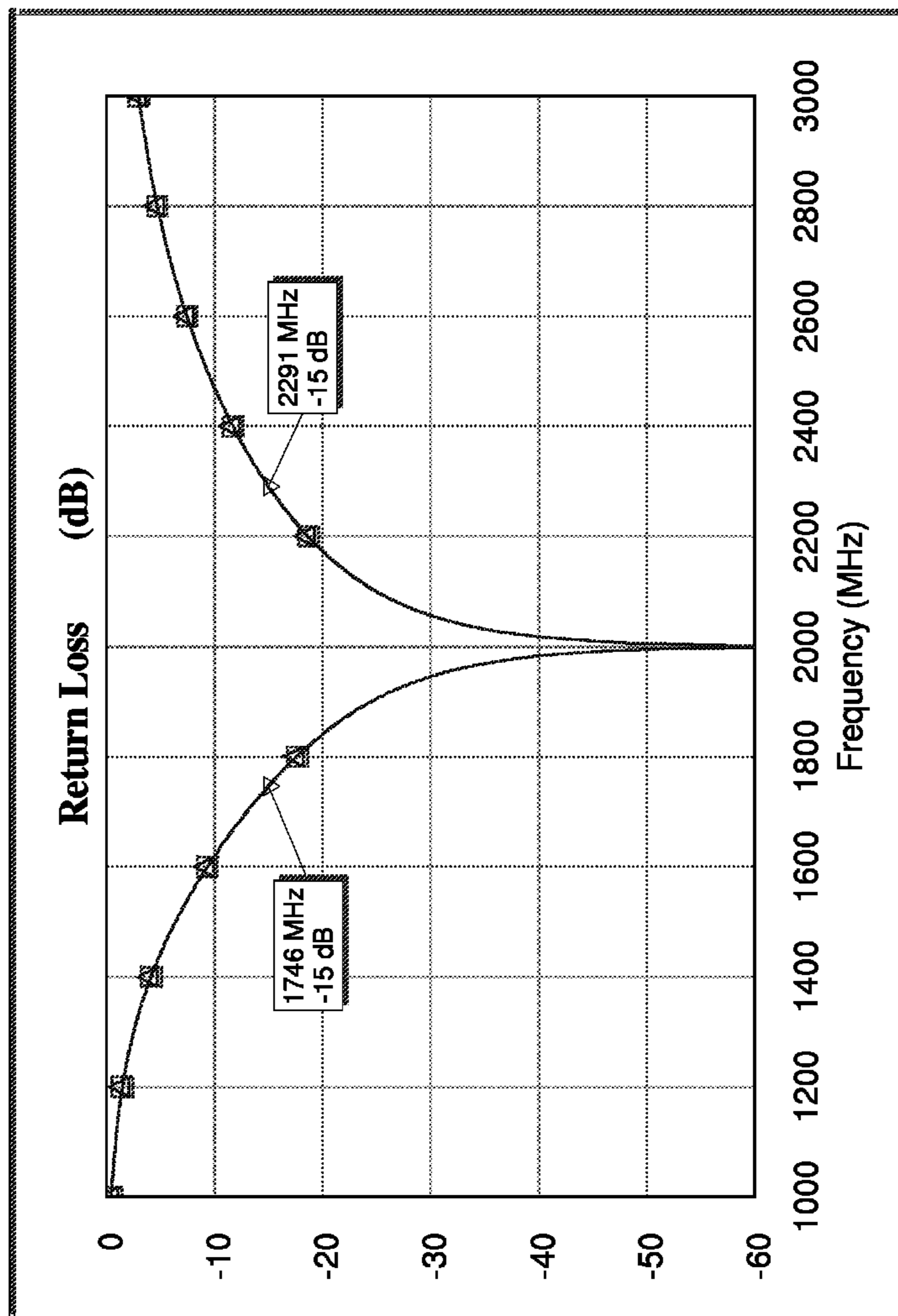


Figure 5

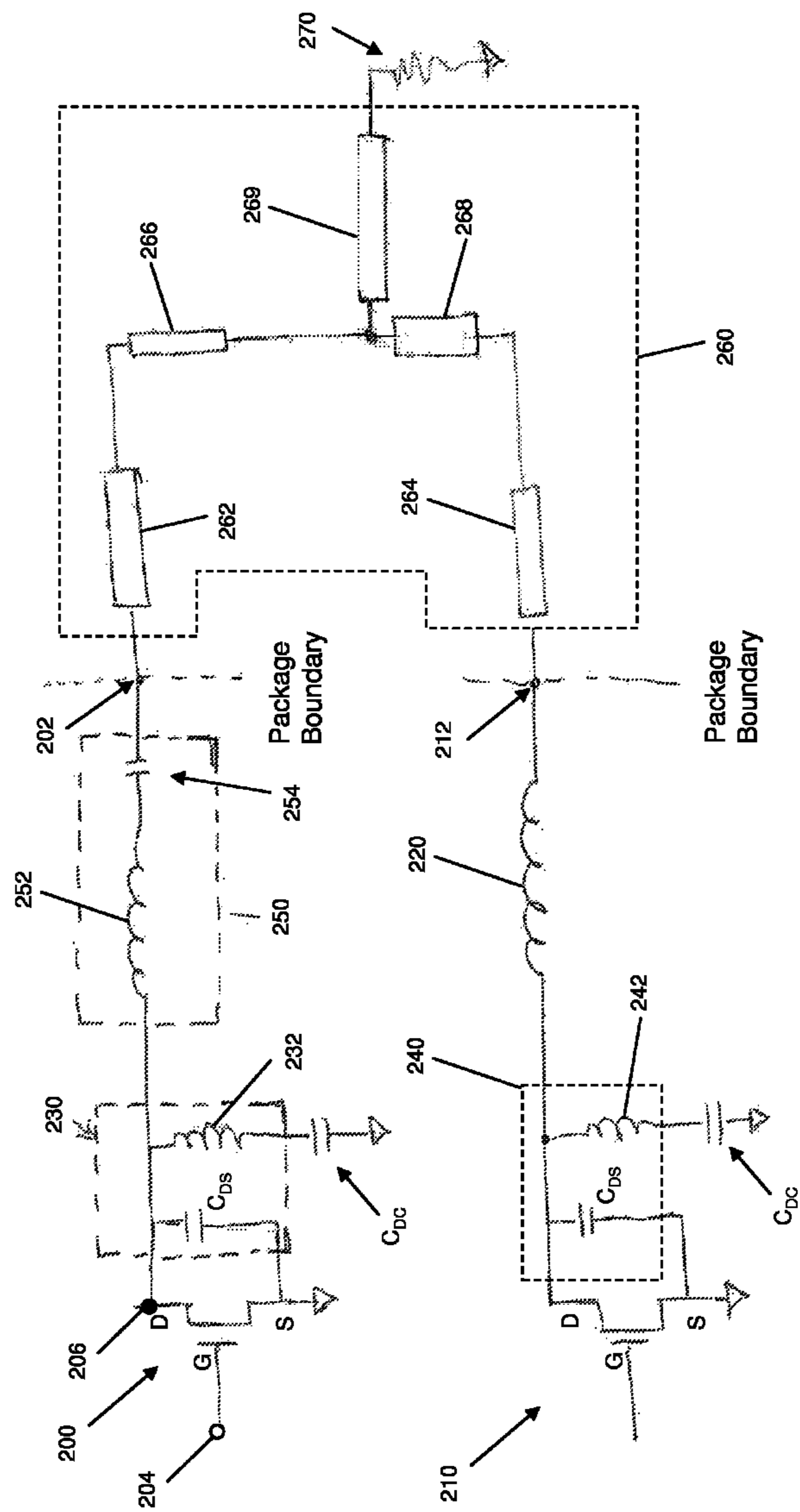


Figure 6

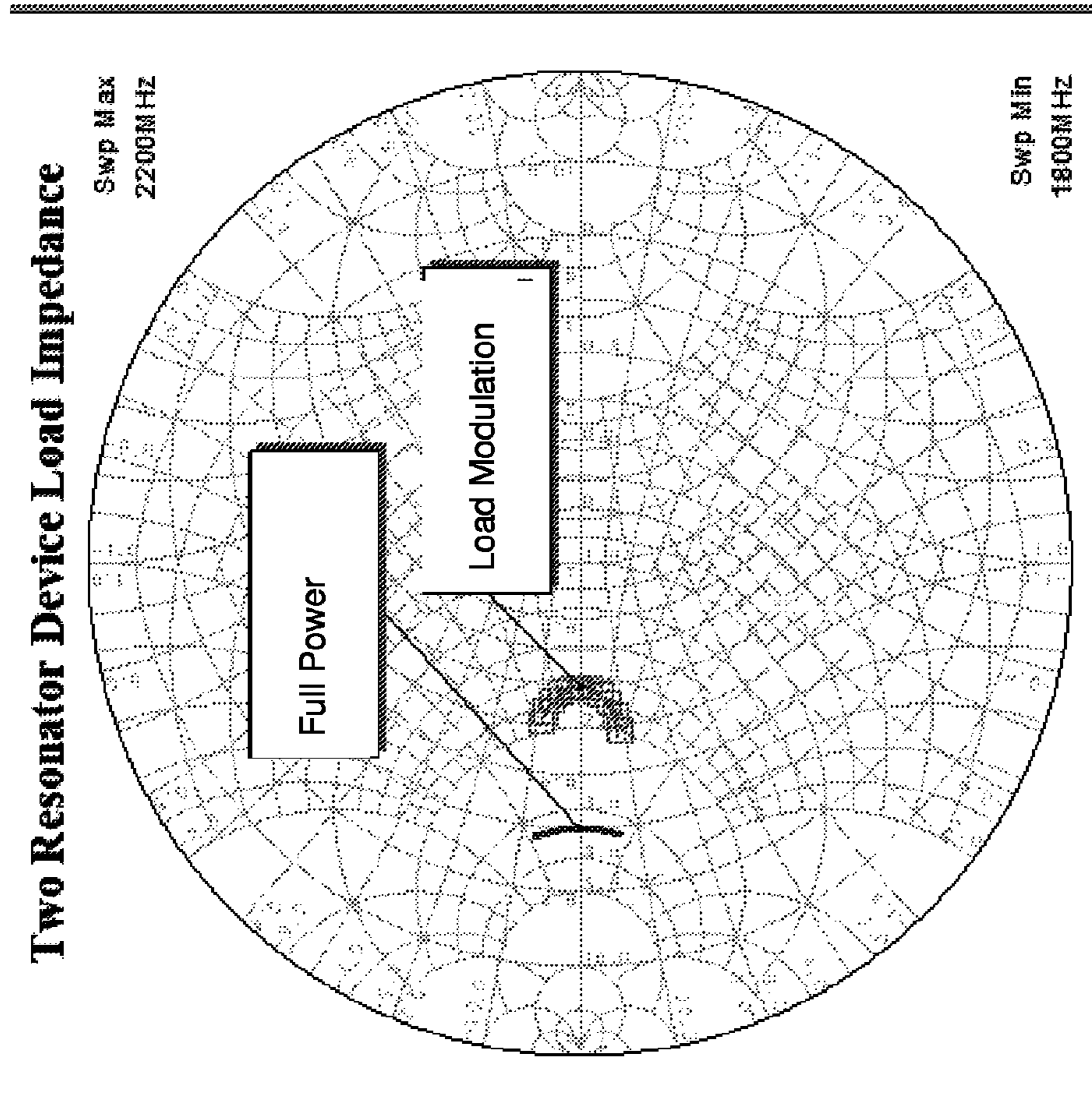


Figure 7

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**RF DEVICE WITH COMPENSATORY
RESONATOR MATCHING TOPOLOGY**

TECHNICAL FIELD

The present application relates to RF devices, in particular RF transistors with an intrinsic output capacitance.

BACKGROUND

Conventional high power, high frequency RF devices typically include an internal shunt inductance matching network for resonating the device intrinsic output capacitance and allowing easier external matching of the device. However such an LC network has frequency limitations because of the inherent resonant nature of the structure. In addition, the high power RF device package uses bond wires for carrying the signal from the die to the package edge. These bond wires introduce undesirable series inductance to the LC matching network, forcing a higher Q match than may be desirable. The Q may be reduced at the package by using an internal lumped shunt inductor followed by an LC low pass matching structure. However such an approach does not allow a perfect real impedance to be presented at the package since an inductive bond wire is provided between the last capacitor and the device output terminal. This approach also provides impedance inversion, and is therefore not transparent to load modulation.

SUMMARY

The embodiments described herein provide a series resonator with inverse characteristics of the parallel resonator typically connected to the output of an RF transistor, so that the response of the parallel resonator over frequency is compensated for by the series resonator. The RF transistor can be tailored to exhibit virtually ideal load contour placement at the center frequency with minimal change over a wide bandwidth due to the compensating nature of the two resonators. This allows an amplifier to be designed with wideband structures such as Klopfenstein tapered lines, and allows use of a wideband Doherty combining network, among other applications. The embodiments described herein also provide enhanced bandwidth for fixed load applications.

According to an embodiment of an amplifier circuit, the circuit includes an RF transistor, a parallel resonator and a series resonator. The RF transistor has an input, an output and an intrinsic output capacitance. The parallel resonator is connected to the output of the RF transistor and includes a first inductive component coupled in parallel with the intrinsic output capacitance of the RF transistor. The series resonator connects the output of the RF transistor to an output terminal and includes a second inductive component connected in series with a capacitive component. The series resonator is operable to compensate for a change in impedance of the parallel resonator over frequency.

According to an embodiment of a method of operating an amplifier circuit, the method includes: amplifying a signal input to an RF transistor also having an output and an intrinsic output capacitance; coupling a first inductive component in parallel with the intrinsic output capacitance of the RF transistor to form a parallel resonator coupled to the output of the RF transistor; coupling the output of the RF transistor to an output terminal via a series resonator which includes a second inductive component connected in series with a capacitive component; and compensating for a change in impedance of the parallel resonator over frequency via the series resonator.

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According to another embodiment of an amplifier circuit, the circuit includes an RF transistor, a parallel resonator and a series resonator. The RF transistor has an input, an output and an intrinsic output capacitance. The RF transistor is operable to function at a first load impedance in a load modulation mode and at a second lower load impedance in a full power mode. The parallel resonator is connected to the output of the RF transistor and includes a first inductive component connected in parallel with the intrinsic output capacitance of the RF transistor. The series resonator connects the output of the RF transistor to an output terminal and includes a second inductive component connected in series with a capacitive component. The series resonator in conjunction with the parallel resonator is operable to maintain a real load impedance for the RF transistor in both the load modulation mode and the full power mode for the same frequency.

According to an embodiment of a Doherty amplifier circuit, the circuit includes a first output terminal, a second output terminal, a main amplifier, a peaking amplifier, a parallel resonator and a series resonator. The main amplifier is biased at Class B or AB mode and has an input, an output and an intrinsic output capacitance. The main amplifier is operable to function at a first load impedance in a load modulation mode and at a second lower load impedance in a full power mode. The peaking amplifier is biased at Class C mode and electrically connected to the second output terminal. The parallel resonator is connected to the output of the main amplifier and includes a first inductive component connected in parallel with the intrinsic output capacitance of the main amplifier. The series resonator connects the output of the main amplifier to the first output terminal and includes a second inductive component connected in series with a capacitive component. The series resonator in conjunction with the parallel resonator is operable to maintain a real load impedance for the main amplifier in both the load modulation mode and the full power mode for the same frequency.

Those skilled in the art will recognize additional features and advantages upon reading the following detailed description, and upon viewing the accompanying drawings.

BRIEF DESCRIPTION OF THE FIGURES

The elements of the drawings are not necessarily to scale relative to each other. Like reference numerals designate corresponding similar parts. The features of the various illustrated embodiments can be combined unless they exclude each other. Embodiments are depicted in the drawings and are detailed in the description which follows.

FIG. 1 illustrates a circuit diagram of an amplifier circuit including an RF transistor, a parallel resonator and a series resonator.

FIG. 2 illustrates a Smith chart of the individual impedances of the parallel resonator and series resonator shown in FIG. 1.

FIG. 3 illustrates a Smith chart of the combined impedance of the parallel resonator and series resonator shown in FIG. 1.

FIG. 4 illustrates a plot diagram of the bandwidth response of the reactive elements of an amplifier circuit which includes an RF transistor, a parallel resonator and a series resonator for a fixed load impedance.

FIG. 5 illustrates a plot diagram of the bandwidth response of the reactive elements of an amplifier circuit which includes an RF transistor, a parallel resonator and a series resonator for a modulated load impedance.

FIG. 6 illustrates a circuit diagram of a Doherty amplifier circuit including a main amplifier with a parallel resonator and a series resonator.

FIG. 7 illustrates a Smith chart of the load impedance of the main amplifier circuit shown in FIG. 6.

DETAILED DESCRIPTION

FIG. 1 illustrates an embodiment of an amplifier circuit which includes an RF transistor **100**, a parallel resonator **110** and a series resonator **120**. The RF transistor **100** has an input **102**, an output **104** and an intrinsic output capacitance (C_{DS}). The RF transistor **100** amplifies a signal provided at the transistor input **102**. The RF transistor **100** may operate in fixed load applications where the load impedance on the transistor remains constant. The RF transistor **100** may also operate in load modulated applications where the load impedance on the transistor **100** is higher at low power settings to improve efficiency and is lower at full power. In one embodiment, the RF transistor **100** is an LDMOS (laterally diffused metal oxide semiconductor) transistor where the gate (G) of the LDMOS transistor is the input **102**, the drain (D) is the output **104** and the intrinsic output capacitance is referenced between the drain and source (S) **106** of the transistor **100**. In another embodiment, the RF transistor **100** is a GaN MESFET (metal semiconductor field effect transistor), GaAs HBT (heterojunction bipolar transistor), PHEMT (pseudomorphic high electron mobility transistor), or other type of transistor. GaN has an inherently lower parasitic output capacitance for a comparable power device compared to silicon technologies. The GaN MESFET like the LDMOS transistor has a gate (G) as the input **102**, a drain (D) as the output **104** and the intrinsic output capacitance is referenced between the drain and source. The transistor source **106** may be connected to ground or some other potential. Other types or configurations of transistors may be used instead e.g. such as a heterojunction bipolar transistor or any other type of RF power transistor.

In each case, the parallel resonator **110** is connected to the output **104** (drain in FIG. 1) of the RF transistor **100**. The parallel resonator **110** includes an inductive component **112** coupled in parallel with the intrinsic output capacitance C_{DS} of the RF transistor **100**. The transistor **100** shown in FIG. 1 is an LDMOS or GaN MESFET transistor and therefore the inductive component **112** of the parallel resonator **110** is coupled in parallel with the intrinsic output capacitance between the drain and ground. In one embodiment, the inductive component **112** of the parallel resonator **110** is a tuning bond wire and a DC blocking capacitor (C_{DC}) is connected in series with the tuning bond wire to prevent an undesirable DC path to ground at the transistor output **104**.

Also connected to the output **104** of the RF transistor **100** is the series resonator **120**. The series resonator **120** connects the transistor output **104** to an output terminal **130** of the amplifier circuit (e.g. at the edge of a package which includes the amplifier circuit). The series resonator **120** includes an inductive component **122** connected in series with a capacitive component **124**. In one embodiment, the inductive component **122** of the series resonator **120** is a bond wire which couples the output **104** of the RF transistor **100** to the capacitive component **124** which can be an RF MOS capacitor. The series resonator **120** compensates for a change in the impedance of the parallel resonator **110** over frequency. While the series resonator **120** does not reduce the Q of the parallel resonator **110**, the series resonator **120** does enable a 'real' optimal load impedance for the RF transistor **100** because the parasitic inductance of the drain bond wire is absorbed into the inductive component **122** of the series resonator **120**. Accordingly, the RF transistor **100** can essentially have ideal 'real' impedance load contours and a much lower Q is provided at the packaged device level. The series resonator **120**

also provides compensation over frequency to the parallel resonator **110** which is present in large RF power devices, enabling a wide bandwidth to be achieved.

FIG. 2 shows a Smith chart of the individual impedances of the parallel resonator **110** and the series resonator **120** over a frequency sweep of 2000 MHz for a particular set of device parameters. The impedance of the parallel resonator **110** is represented by the curve labelled 'parallel resonator' and the impedance of the series resonator **120** is represented by the curve labelled 'series resonator' in FIG. 2. The parallel resonator **110** becomes less inductive as the frequency increases and eventually becomes capacitive at high enough frequencies as indicated by the generally downward facing arrows included along the curve labelled 'parallel resonator' in FIG. 2 (the downward arrows indicating increasing frequency). To compensate for this response of the parallel resonator **110** which would otherwise adversely affect bandwidth if left unmitigated, the series resonator **120** becomes more inductive as the frequency increases as indicated by the generally upward facing arrows included along the curve labelled 'series resonator' in FIG. 2. The opposite response occurs when the frequency decreases, that is the parallel resonator **110** becomes more inductive and the series resonator **120** becomes less inductive. The series resonator **120** is thus designed to counterbalance, offset or otherwise at least partly counteract the change in inductivity of the parallel resonator **110** over frequency.

FIG. 3 shows a Smith chart of the combined impedance of both resonators **110**, **120** over the frequency sweep as in FIG. 2 and for the same set of device parameters. The compensating influence of the series resonator **120** on the impedance of the parallel resonator **110** over frequency results in a combined load impedance for the RF transistor **100** which folds in toward the real axis over a wider frequency range as compared to the same circuit without the series resonator **120**. Such a folded response enhances the bandwidth of the amplifier circuit, making it well suited for wideband applications. Various simulations show the bandwidth of the amplifier circuit is at least 1.5× greater with the series resonator **120** than without the series resonator **120**.

FIG. 4 shows the return loss (in dB) over frequency for an exemplary LDMOS transistor die with a 30 pF intrinsic output capacitance running into a fixed optimum load impedance. In this fixed load impedance example, the exemplary LDMOS transistor provides a bandwidth of about 1142 MHz with the series resonator **120** included in the circuit and a bandwidth of about only 639 MHz without the series resonator **120** (bandwidth being measured at -15 dB return loss point in this example). Including the series resonator **120** in this exemplary circuit yields a 1.8× bandwidth enhancement. The bandwidth enhancement remains about 1.8× (with the series resonator) irrespective of die size and parasitic/die periphery.

FIG. 5 shows the return loss (in dB) over frequency for the same exemplary 90 mm LDMOS transistor die as described above, but in a load modulated application. The exemplary LDMOS transistor is optimized for 2:1 load modulation in this example (e.g. a 6Ω load modulation mode and 3Ω full power mode). Under such operating conditions, the exemplary LDMOS transistor has a bandwidth of about 545 MHz with the series resonator **120** included in the circuit for both the high impedance load modulation mode and the low impedance full power mode (bandwidth being measured at -15 dB return loss point in this example). Without the series resonator **120**, the exemplary LDMOS transistor only has a bandwidth of about 319 MHz in the high impedance load modulation mode, yielding a 1.7× bandwidth enhancement

with the series resonator **120**. The bandwidth enhancement remains about $1.7\times$ irrespective of die size and parasitic/die area.

In one load modulation embodiment, the amplifier circuit of FIG. **1** may be a Doherty amplifier circuit and the RF transistor **100** is the main amplifier of the Doherty amplifier circuit. The RF transistor **100** functions at a first (higher) load impedance in the load modulation mode and at a second (lower) load impedance in the full power mode. The parallel resonator **110** is connected to the output **104** of the RF transistor **100** and includes an inductive component **112** connected in parallel with the intrinsic output capacitance C_{DS} of the RF transistor **100** as previously described herein. The series resonator **120** connects the output **104** of the RF transistor **100** to the output terminal **130** of the main amplifier also as previously described herein. The series resonator **120** in conjunction with the parallel resonator **110** maintains a real load impedance for the RF transistor **100** (the main amplifier in this embodiment) in both the load modulation and full power modes for the same frequency. The series resonator **120** in conjunction with the parallel resonator **110** can also maintain the same bandwidth for the amplifier circuit in the load modulation and full power modes.

FIG. **6** illustrates an embodiment of a Doherty amplifier circuit for use in load modulated applications. The Doherty amplifier circuit includes a main amplifier **200**, an output terminal **202** for the main amplifier **200**, a peaking amplifier **210**, and an output terminal **212** for the peaking amplifier **210**. The main amplifier **200** is biased at Class B or AB mode and has an input **204**, an output **206** and an intrinsic output capacitance (C_{DS}). The peaking amplifier **210** is biased at Class C mode and electrically connected to the output terminal **212** via e.g. a bond wire **220**. Both amplifiers **200**, **210** have a parallel resonator **230**, **240** connected to the output of the respective amplifiers **200**, **210**. Each parallel resonator **230**, **240** has an inductive component **232**, **242** such as a tuning bond wire connected in parallel with the intrinsic output capacitance C_{DS} of the corresponding amplifier **200**, **210**. A DC blocking capacitor (C_{DC}) may be connected in series with each respective tuning bond wire **232**, **242**.

The Doherty amplifier circuit also includes a series resonator **250** which connects the output **206** of the main amplifier **200** to the output terminal **202** for the main amplifier **200**. The series resonator **250** includes an inductive component **252** such as a bond wire connected in series with a capacitive component **254** such as an RF MOS capacitor.

The main amplifier **200** functions at a first (higher) load impedance in a load modulation mode and at a second lower load impedance in a full power mode. At low power levels, only the main amplifier **200** is operational. The efficiency of the main amplifier **200** increases as the power level increases. The main amplifier **200** eventually reaches a maximum efficiency point as the power level continues to rise. At this power level, the peaking amplifier **210** turns on. The efficiency of the peaking amplifier **210** similarly increases for power levels above this point. One or more additional peaking amplifiers can be provided. The series resonator **250** in conjunction with the parallel resonator **230** of the main amplifier **200** maintains a real load impedance for the main amplifier **200** in both the load modulation mode and the full power mode for the same frequency. The series resonator **250** in conjunction with the parallel resonator **230** can also maintain the same bandwidth for the Doherty amplifier circuit in the load modulation mode and the full power mode if desired as previously explained herein.

The amplifier output terminals **202**, **212** are at the package boundary, meaning external connections are made to these

terminals **202**, **212**. A Doherty combining network **260** which can be a wideband combiner in some applications, can be connected to the amplifier output terminals **202**, **212** for connecting the Doherty amplifier circuit to a load **270**. The Doherty combining network **260** combines or sums the load currents of the amplifiers **200**, **210** so that the output voltage of the Doherty amplifier circuit is determined by the summation of the load currents multiplied by the load impedance. For example, the Doherty combining network **260** can have an output matching circuit **262** connected to the main amplifier output terminal **202** and another output matching circuit **264** connected to the peaking amplifier output terminal **212**. A first power combiner **266** connects the first output matching circuit **262** to an impedance transformer **269** and a second power combiner **268** connects the second output matching circuit **264** to the same node of the impedance transformer **269**. The other node of the impedance transformer **269** is connected to the load **270**. The impedance combiner **269** may have a tapered shape with a wider end coupled to the power combiners **266**, **268** and a narrower end connected to the load **270** or vice-versa. During operation for example, the impedance transformer **269** can transform the load impedance at one terminal to a transformed impedance at the other terminal which matches (i.e. identically or nearly identically) the impedance of the first and second power combiners **266**, **268**. Alternatively, other types of Doherty combining networks can be used.

FIG. **7** shows a Smith chart of the combined load impedance of the parallel and series resonators **230**, **250** coupled to the main amplifier **200** over a frequency sweep of 400 MHz. The combined load impedance for the main amplifier **200** in the load modulated mode is represented by the curve labelled 'load modulation' and the combined load impedance for the main amplifier **200** in the full power mode is represented by the curve labelled 'full power' in FIG. **7**. The combined load impedance for the main amplifier **200** falls on the real axis in both the load modulated mode and the full power mode for the same center frequency. In FIG. **7**, this frequency is 2000 MHz and the real impedance is 6Ω in the load modulated mode and 3Ω in the full power mode. Without the series resonator **250**, the main amplifier load impedance would always fall in the capacitive region of the Smith chart because of the drain bond wire inductance. This bond wire inductance is absorbed by the series resonator **250** when included in the circuit. This enables optimum performance to be obtained using wideband impedance transformers such as a Klopfenstein taper.

Terms such as "first", "second", and the like, are used to describe various elements, regions, sections, etc. and are not intended to be limiting. Like terms refer to like elements throughout the description.

As used herein, the terms "having", "containing", "including", "comprising" and the like are open ended terms that indicate the presence of stated elements or features, but do not preclude additional elements or features. The articles "a", "an" and "the" are intended to include the plural as well as the singular, unless the context clearly indicates otherwise.

It is to be understood that the features of the various embodiments described herein may be combined with each other, unless specifically noted otherwise.

Although specific embodiments have been illustrated and described herein, it will be appreciated by those of ordinary skill in the art that a variety of alternate and/or equivalent implementations may be substituted for the specific embodiments shown and described without departing from the scope of the present invention. This application is intended to cover any adaptations or variations of the specific embodiments

discussed herein. Therefore, it is intended that this invention be limited only by the claims and the equivalents thereof.

What is claimed is:

1. An amplifier circuit, comprising:
an RF transistor having an input, an output and an intrinsic capacitance;
a parallel resonator coupled to the output of the RF transistor and comprising a first inductive component coupled in parallel with the intrinsic capacitance of the RF transistor; and
a series resonator coupling the output of the RF transistor to an output terminal and comprising a second inductive component connected in series with a capacitive component, the series resonator having inverse impedance characteristics of the parallel resonator with respect to a single center frequency of the RF transistor so that the series resonator is operable to counteract a change in impedance of the parallel resonator over a wideband frequency range of the RF transistor.
2. An amplifier circuit according to claim 1, wherein the first inductive component is a tuning bond wire coupling the output of the RF transistor to a DC blocking capacitor and the second inductive component is a bond wire coupling the output of the RF transistor to an RF MOS capacitor which forms the capacitive component of the series resonator.
3. An amplifier circuit according to claim 1, wherein the RF transistor is an LDMOS transistor.
4. An amplifier circuit according to claim 1, wherein the RF transistor is a GaN MESFET.
5. An amplifier circuit according to claim 1, wherein the parallel resonator is operable to become less inductive and the series resonator is operable to become more inductive as the frequency decreases, and the parallel resonator is operable to become more inductive and the series resonator is operable to become less inductive as the frequency increases.
6. An amplifier circuit according to claim 1, wherein a bandwidth of the amplifier circuit is at least 1.5× greater with the series resonator than without the series resonator.
7. An amplifier circuit according to claim 6, wherein the bandwidth of the amplifier circuit is at least 1.7× greater with the series resonator than without the series resonator.
8. An amplifier circuit according to claim 1, wherein the amplifier circuit is a Doherty amplifier circuit and the RF transistor is a main amplifier of the Doherty amplifier circuit.
9. A method of operating an amplifier circuit, comprising:
amplifying a signal input to an RF transistor also having an output and an intrinsic capacitance;
coupling a first inductive component in parallel with the intrinsic capacitance of the RF transistor to form a parallel resonator coupled to the output of the RF transistor;
coupling the output of the RF transistor to an output terminal via a series resonator which includes a second inductive component connected in series with a capacitive component, the series resonator having inverse impedance characteristics of the parallel resonator with respect to a single center frequency of the RF transistor; and

counteracting a change in impedance of the parallel resonator over a wideband frequency range of the RF transistor via the series resonator.

10. A method according to claim 9, wherein a change in impedance of the parallel resonator over frequency is counteracted via the series resonator by:

decreasing the inductivity of the parallel resonator and increasing the inductivity of the series resonator as the frequency decreases; and

increasing the inductivity of the parallel resonator and decreasing the inductivity of the series resonator as the frequency increases.

11. An amplifier circuit, comprising:
an RF transistor having an input, an output and an intrinsic capacitance, the RF transistor being operable to function at a first load impedance in a load modulation mode and at a second lower load impedance in a full power mode;
a parallel resonator coupled to the output of the RF transistor and comprising a first inductive component coupled in parallel with the intrinsic capacitance of the RF transistor; and
a series resonator coupling the output of the RF transistor to an output terminal and comprising a second inductive component connected in series with a capacitive component, the series resonator having inverse impedance characteristics of the parallel resonator with respect to a single center frequency of the RF transistor so that the series resonator in conjunction with the parallel resonator are operable to maintain a real load impedance for the RF transistor in both the load modulation mode and the full power mode for the same frequency.

12. An amplifier circuit according to claim 11, wherein the series resonator in conjunction with the parallel resonator are operable to maintain the same bandwidth for the amplifier circuit in the load modulation mode and the full power mode.

13. An amplifier circuit according to claim 11, wherein the first inductive component is a tuning bond wire coupling the output of the RF transistor to a DC blocking capacitor and the second inductive component is a bond wire coupling the output of the RF transistor to an RF MOS capacitor which forms the capacitive component of the series resonator.

14. An amplifier circuit according to claim 11, wherein the RF transistor is an LDMOS transistor.

15. An amplifier circuit according to claim 11, wherein the RF transistor is a GaN MESFET.

16. An amplifier circuit according to claim 11, wherein the parallel resonator is operable to become less inductive and the series resonator is operable to become more inductive as the frequency decreases, and the parallel resonator is operable to become more inductive and the series resonator is operable to become less inductive as the frequency increases.

17. An amplifier circuit according to claim 11, wherein a bandwidth of the amplifier circuit is at least 1.5× greater with the series resonator than without the series resonator.